Assessment of the Effectiveness of Prelaunch Temperature Testing and Analysis for Unmanned Outer Planet Spacecraft

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ABSTRACT

In the last thirty years, seven unmanned planetary spacecraft have been designed, ground tested and flown to astronomical distances of five (5) astronomical units and beyond. These include two Pioneer spacecraft (Pioneers 10 and 11), Voyagers 1 and 2, Galileo, Ulyssess, and Cassini. These missions include flybys, planetary orbiters, and atmospheric probes. The thermal design approach applied to these spacecraft is based on the passive thermal designs applied to the earlier Pioneer, Ranger, and Mariner lunar and interplanetary spacecraft. The ground test and analysis programs are based on that heritage. The in flight temperature data from representative sets of engineering subsystems and science instruments from four of these spacecraft are compared to those obtained during the ground test programs and from the prelaunch predictions. Included in the assessment is a description of the technology used in the electronics and of the thermal aspects of the packaging. This information is used to evaluate how strongly evolving technology and packaging influences the ground test and analysis programs for the new generations of outer planet spacecraft and to evaluate the magnitude of temperature excursions observed during duty cycling in flight. Several lessons are presented with specific recommendations for considerations for new projects to aid in the planning of cost effective temperature design, test, and analysis programs.

1. INTRODUCTION

The initial exploration of the outer planets (Jupiter, Saturn, Uranus, and Neptune) using unmanned remote sensing spacecraft has occurred during the latter part of the 20^{th} century and continues in the early part of the 21^{st} century. The scientific data obtained has included spectacular pictures of Jupiter and its bands and of Saturn and its rings. These long life deep space missions represent the efforts of numerous scientists and engineers throughout the world during the design, development, and operations phases. The electronic technology used in the designs for Voyager, Galileo, and Cassini spacecraft as well as the environmental test programs implemented [1][2] evolved over the twenty year period that brackets the spacecrafts' development phases: 1972 to 1993.

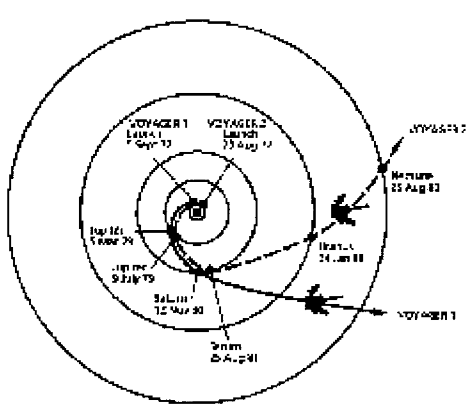
2. MISSION AND TECHNOLOGY DESCRIPTIONS

2.1 Spacecraft and Mission Descriptions

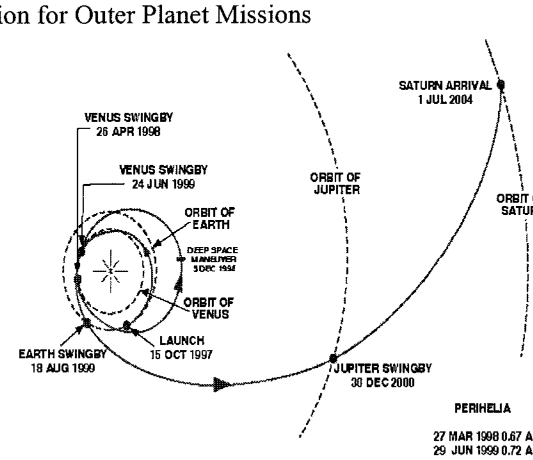
Some key aspects of the Voyager, Galileo and Cassini spacecraft and missions are summarized in Table 1. The primary power sources for these missions are Radioisotope Thermoelectric Generators (RTGs). Some of the supplemental heat for temperature control purposes is provided by electrical heaters and Radioisotope Heater Units (RHUs). Examples of mission trajectories for Voyager and Cassini are given in Figure 1a and 1b. The Voyager trajectories are examples of direct flights from Earth to the outer planets and then using gravity assists from the outer planets to perform the Grand Tour. The Cassini trajectory is an example of a trajectory that uses gravity assists from flybys of the inner planets (Earth, Venus) as well as Jupiter to obtain sufficient energy for the transit to Saturn.

Attribute	Voyager		Galileo Orbiter	Cassini Orbiter
	1	2		
Spacecraft				
Power Source	RTG (3) (Multihundred watt)	RTG (3) (Multihundred watt)	RTG (2) (General Purpose Heat Source)	RTG (3) (General Purpose Heat Source)
Beginning of Mission May 2001	480 watts 316 watts	480 watts 320 watts	570 watts 449 watts	880 watts 787 watts
Science Instruments	10	10	9 Orbiter 6 Probe	12 Orbiter 6 Huygens Probe
Mass	815 Kg (1797 lb)	815 Kg (1797 lb)	2561 Kg (5646 lb)	5800 Kg (12,800 lb)
Temperature Control Design	Passive, louvers, RHUs, electrical heaters	Passive, louvers, RHUs, electrical heaters	Passive, louvers, RHUs, electrical heaters, closed loop computer controlled heaters	Passive, louvers, RHUs, electrical heaters, closed loop computer controlled heaters
Temperature Control Operations	Active Sequence of Heating	Active Sequence of Heating	Pointing Constrained for Shading Bus Shade (and local shading)	Pointing Constrained for Shading (high gain antenna)
Solar Distances Design Range	1AU to 10 AU	1AU to 10 AU	0.6 AU to 5 AU	0.67 AU to 10 AU
Primary Mission Design Life	Through Saturn encounter	Through Saturn encounter	Five (5) Jovian orbits	11 years
Mission				
Launch Vehicle	Expendable Titan IIIE, Centaur	Expendable Titan IIIE, Centaur	Shuttle w/ Inertial Upper Stage	Expendable Titan IVB, Centaur G
Mission Type	Flyby	Flyby	Orbiter with probe	Orbiter with probe
Destination	Jupiter and Saturn	Jupiter and Saturn	Jupiter	Saturn
Launch Date Gravitational assists from	1977 Jupiter Saturn	1977 Jupiter Saturn Neptune Uranus	1989 Venus Earth (2)	1997 Venus (2) Earth Jupiter
Distance from Sun AU (June, 2001)	81	64	5.2	6.3

Table 1. Spacecraft and Mission for Outer Planet Missions



a)Voyager



b) Cassini

Figure 1 Representative Mission Trajectories for Outer Planet Missions using Gravity Assist

2.2 Spacecraft Subsystems Technology

An overview of the technology applied to each spacecraft is given in Table 2. The early unmanned lunar and inner planets spacecraft (1961-1975 eg Rangers, Mariners, Viking) used an approach for packaging used a magnesium housing in the shape of "tub" to mount the "modules" with the resulting "bay" then attached to the spacecraft structure. The packaging of the electronics for the outer planets spacecraft utilized the dual shear plate design. This design consists of inner and outer mounting plates of honeycomb material with coversheets to which the circuit boards were attached and the edges of the shear plates were attached to the spacecraft. The dual shear plate mounting approach was used to reduce the mass of the electronic housing. The technology applied to the onboard computers evolved from CMOS memories (early 1970's) of approximately 0.001 millions of instructions per second (MIPS) to the CMOS memories of the late 1980's that supported 0.1 MIPS, a thousand fold increase, Table 2b [3]. Other significant changes included for data storage tape recorders to solid state recorders with the on board capability of storing 5.1 x 10^8 bits for Voyager to 1.8 x 10^9 bits for Cassini. For the imaging science experiments the sensor evolved from a vidicon tube to charged couple device (CCD). As the technology applied evolved, the detailed packaging designs were adapted to accommodate them. However, the environmental test and analysis programs implemented at the "black box" level and at the spacecraft level for Voyager, Galileo and Cassini programs were similar. The overall verification program is summarized in Table 3.

Table 2 Spacecraft Subsystems Technology
a) Overview Examples

Engineering Subsystems	Vintage	Voyager 1 & 2 Early 70's	Galileo Late 70's	Cassini Mid 80's
Electronics	Power	Power & Pyro Subsystem /Relays	Power & Pyro Subsystem /Relays	Power & Pyro Subsystem /Solid State Power Switches
	Telecommunications	S&X Traveling Wave Tube Amplifiers (TWTA)	S&X TWTAs	S&X TWTAs
	Command and Data Handling	Central Computer and Sequencer/ Flight Data Subsystem	Command Data Subsystem	Command Data Subsystem
	Data Storage	Tape Recorder	Tape Recorder	Solid State Recorder
Sensors	Star Trackers	Canopus Tracker	Star Tracker	Stellar Reference Unit
Science Payload				
Instruments	Imaging	Imaging Science Subsystem/Vidicons	Solid State Imaging/Charged Couple Devices (CCDs)	Imaging Science Subsystem/CCDs
	Ultraviolet Spectrometers	Ultraviolet Spectrometer	Extreme Ultraviolet; Ultraviolet Spectrometer	Ultraviolet Imaging Spectrograph
	Infrared Spectrometers	Infrared Interferometer Spectrometer	Near Infrared Mapping Spectrometer	Composite Infrared Spectrometer; Visible and Infrared Mapping Spectrometer

Table 2 Spacecraft Subsystems Technology
b) Detail Examples-Engineering Subsystems

Vintage	Voyager 1 & 2 Early 70's	Galileo Late 70's	Cassini Mid 80's
Engineering Computers Architecture	Central	Distributed	Distributed
Number (inc. redundancy)	6	10	6
Memory Type	Plated wire Memory (4) CMOS (2)	CMOS (TCC244)	CMOS (DRAM)
Word size	18 bit word (4) 16 bit word (2)	CDS: 8 bit word (6) AACS: 16 bit word (4)	16 bit word
	4K words (4) 2K words (4)	CDS: 192K words/string AACS: 3 K words/string	572K words
Data Storage	5.1×10^8 bits	9×10^8 bits	1.8×10^9 bits
Type	Tape recorder Dual redundant	Tape recorder Single string	Solid state recorder Dual redundant
Communications Links	S band up and down X band down	S band up and down X band down (planned)	X band up and down
Probe		S band	S band
Radio Science/Radar			S band down (carrier only) Ka band down (carrier only) Ku band down (carrier only)
TWTA RF Output Power (max) X Band S Band	10/20 watts 10/28 watts	10/20 watts 10/28 watts	20 watts 10 watts
Data Rates Range (bits/s=bps)	16 bps to 1400 bps 115.2 kbps@Jupiter	10 bps to 134.4 kbps@Jupiter (Plan w/ high gain antenna) Actual @Jupiter: 160 bps (effective, with source coding with Low Gain Antenna)	5 bps to 142.2 kbps @Saturn

Table 3 Environmental Verification Summary

	Environment	Assembly/ Subsystem	Spacecraft
Test (T)	Dynamics	T	T
	Thermal	T	T
	Electromagnetic Compatibility	T	T
	Magnetics	T	A
Analysis (A)	Electrostatic Discharge	A	--
	Radiation	A	--
	Solid Particles	A	A
	Atomic Oxygen	A	--

2. GROUND TEST PROGRAM

The thermal test program applied to the hardware consisted of the following steps: the assembly/subsystem/spacecraft and detailed designs were developed by the hardware cognizant engineers and systems engineers with support from technical specialists such as packaging, reliability, environmental requirements, temperature control under the overview of the project's spacecraft design team. If special circumstances were identified for a given assembly/subsystem, a thermal development test was planned and implemented. Depending on the concern being addressed, thermal mock-ups or engineering models would be used for the development testing. Typically, thermal mock-ups were applied when addressing temperature control issues. Engineering models and appropriate thermal mock-ups were used when addressing specific electronic performance issues. Agreements were developed among the cognizant engineers, temperature control engineers, and environmental requirements engineers regarding the allowable flight temperature, the qualification test temperatures and, as appropriate, flight acceptance test temperatures.

For these outer planets programs, the following qualification temperature test requirements were applied to hardware at the assembly level:.

75° C for 144h, -20° C for 24h, in a vacuum $\leq 1 \times 10^{-5}$ torr. If a sensor or assembly required tailored requirements to avoid damaging a temperature limited element within the article, the requirements were hot Allowable Flight Temperature +25°C for 144h cold Allowable Flight Temperature –25°C for 24h.

If several flight articles were being built, the flight units would be subjected to a flight acceptance level test (for example Voyager engineering subsystems had a qualification model that was delivered to the proof test model spacecraft and three flight units, two that would fly and a flight spare.) The levels and durations for the flight acceptance level test were:

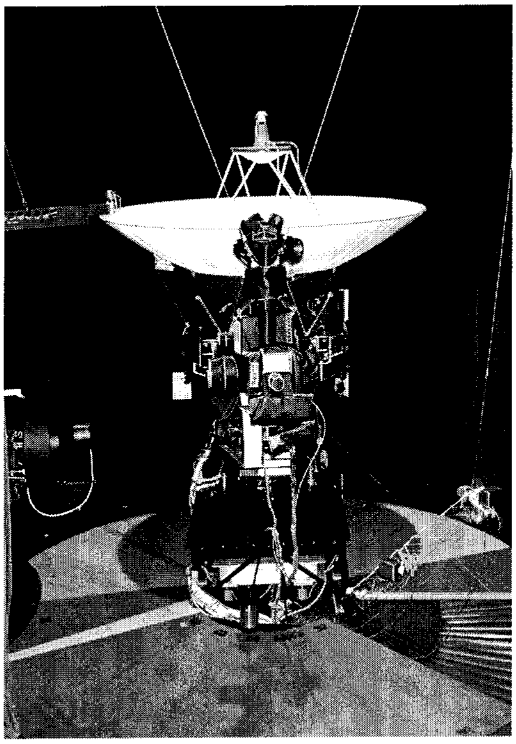
55°C for 60h, 0°C for 8h
or hot AFT +5°C for 60h, cold AFT –5°C for 8h

After integration, the spacecraft was subjected to space simulation testing in JPL's 25 foot space simulator as shown in Figures 3a,b to verify the adequacy of the thermal control of the spacecraft including the thermal control models and to verify satisfactory functional performance of the spacecraft at expected missions with some margin [3, 4, 5]. These temperature results were used to refine the thermal models that were applied by the flight team during flight operations and to specify temperature alarm limits for the readouts of the flight transducers.

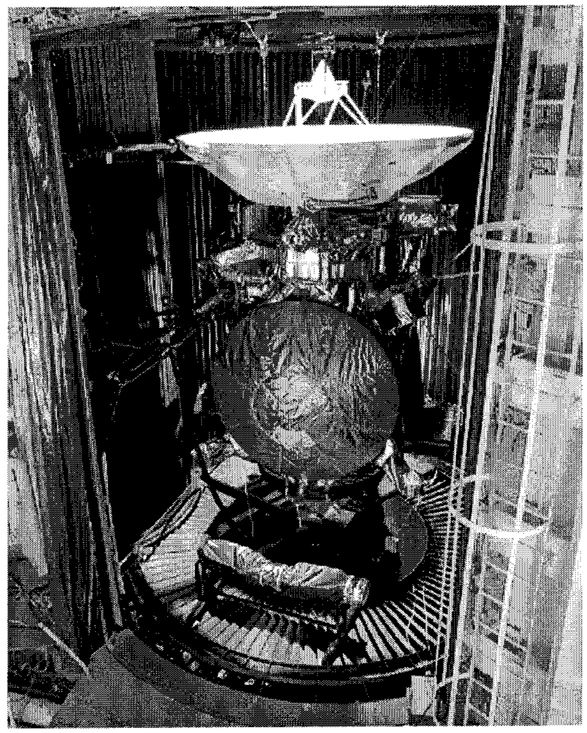
The spacecraft level tests were typically conducted in phases, with chamber breaks scheduled between the phases. If appropriate, changes to thermal blanketing and thermal paints would be performed during the breaks for problems identified during the previous phase. The "fixes" would then be verified in subsequent test.

4. COMPARISONS BETWEEN GROUND TEST AND FLIGHT TEMPERATURES

In flight telemetry data from the Voyager, Galileo and Cassini spacecraft for representative engineering and science and engineering subsystems are provided in Figures 3-6. Each chart displays the in flight temperature range experienced during flight, the ground test qualification test range that was applied, the black box flight acceptance temperature level and a summary of the temperature range noted during solar thermal vacuum testing on the flight spacecraft. The Voyager program was the only one that had a proof test model spacecraft for qualification purposes. Examples of the time histories of temperature in flight are shown in Figures 8 and 9.



Voyager
1977



Cassini
1997

Figure 2. Solar Thermal Vacuum Test Configurations

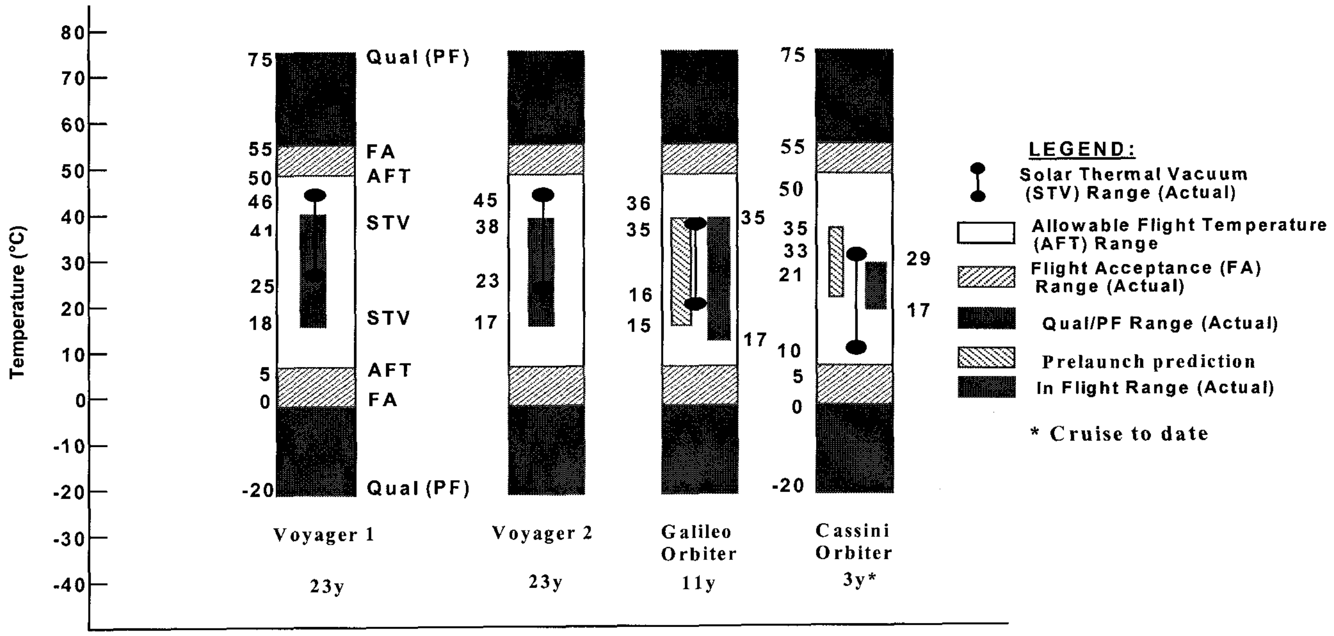


Figure 3
Engineering Subsystems Bus Bays - Comparison between Ground Test and In flight Temperatures
(Allowable Flight Temperature 5°C to 50 °C)

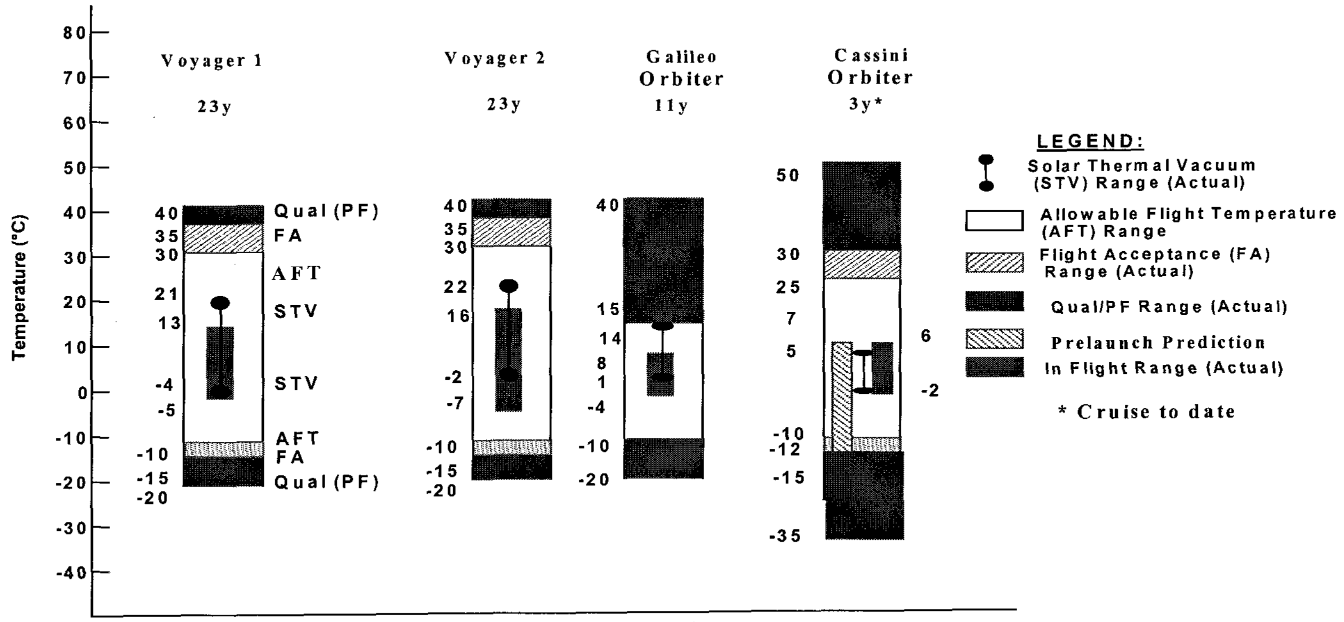


Figure 4
Science Instrument: Imaging Optics – Comparison between Ground Test and In flight Temperature

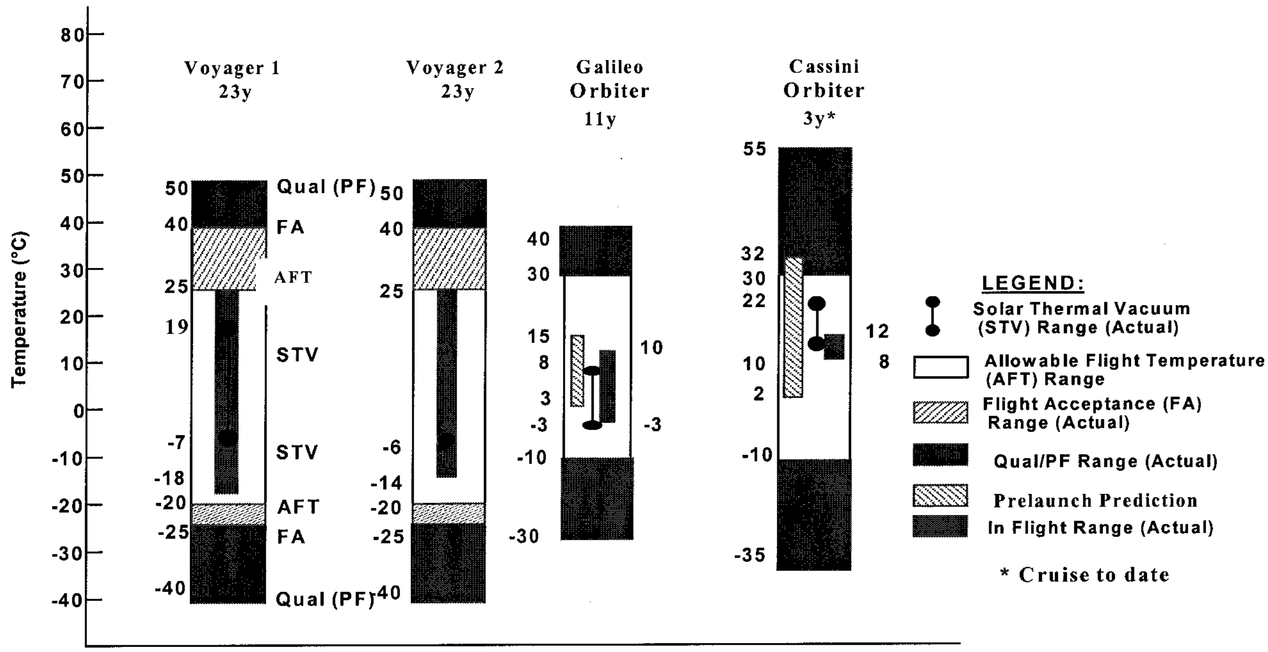


Figure 5
Science Instrument: Ultraviolet Spectrometer – Comparison between
Ground Test and In flight Temperature

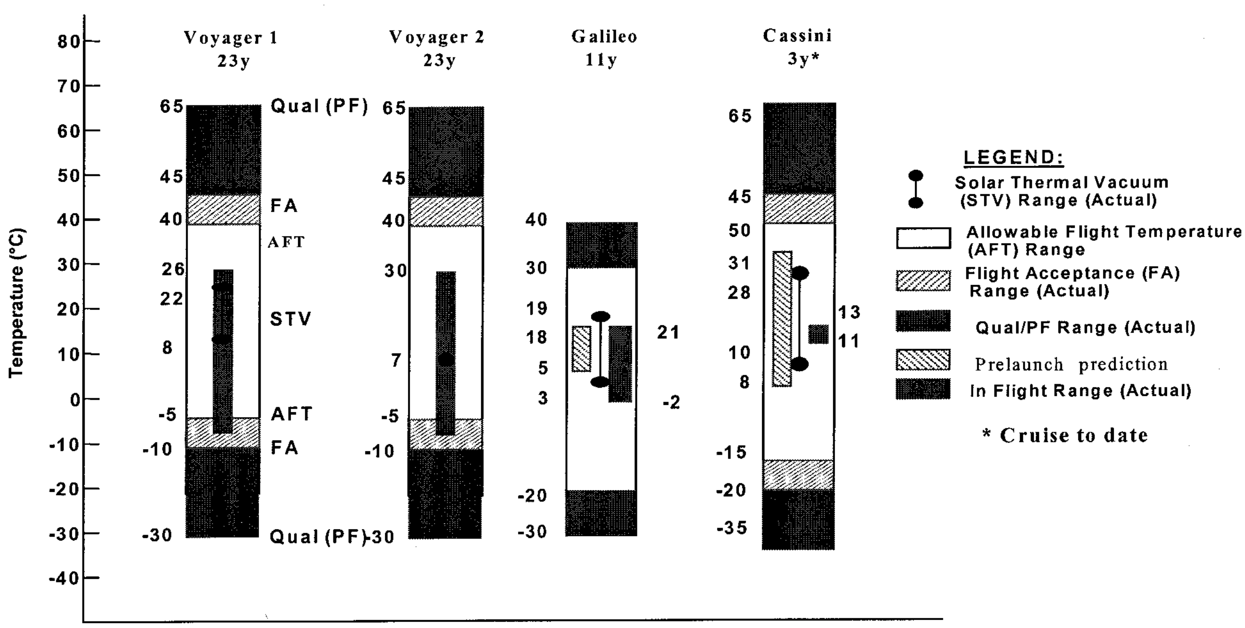


Figure 6
Science Instrument: Infrared Interferometer Spectrometer
Electronics-Comparison between
Ground Test and In flight Temperature

5. DISCUSSION AND ASSESSMENT RESULTS

The spacecraft summaries and the temperature data provided in the previous sections were analyzed for trends to determine the sufficiency of the ground test programs and to determine any lessons learned from these programs that could be applied to future long life missions. The following observations are presented:

There are several examples where the technology changed, with resultant changes in power density and power dissipation in the electronics or the sensors, but the packaging approach was robust enough to accommodate these technology advancements. The lesson learned is that the new packaging concepts should be sufficiently robust in dissipating heat from electronic piece parts such that rapidly changing technology can be incorporated into the circuit board without decreasing reliability.

Solar simulation was necessary for spacecraft level testing especially for Galileo and Cassini whose trajectories included gravity assists at Venus.

The passive thermal design approach worked well for unmanned outer planet flybys and orbiters. All spacecraft thermal designs had to accommodate extendable booms. For missions, flybys and orbiters, designed for beyond 5 AU, passive thermal design are simple and adequate for these types of missions. On board computer controlled heaters can be utilized.

End to end verification of flight temperature telemetry was performed during the system level thermal vacuum tests. These temperature measurements were compared to those from thermocouples mounted in similar locations for the ground instrumentation data system. End to end verification of flight temperature telemetry during ground testing should continue to be one of the objectives of spacecraft level testing.

All of the missions were tested in the JPL twenty five foot Space Simulator. For each of the test programs, the facility had been upgraded and maintained. A core cadre of experienced personnel was available to implement the test programs. For future missions that require solar simulation to verify a spacecraft's thermal design, especially for mission traversing large AU distances from the sun, a well maintained facility with experienced personnel are important assets for a project.

6. SUMMARY

The initial exploration of the outer planets of the solar system has occurred during the last thirty years with unmanned planetary spacecraft that emphasized passive thermal designs. The conservative practices applied to the design and testing efforts has lead to an effective demonstration of long life reliability. The ground testing programs applied to all of these missions are characterized by: a) thermal development test activity for areas where there were significant thermal uncertainties, b) rigorous "blackbox level" environmental temperature testing program (qualification/protoflight /flight acceptance) for the electronics and mechanisms typically with long dwells and in vacuum, and c) comprehensive solar thermal vacuum test program on the flight spacecraft where not only was the thermal design verified but overall spacecraft performance. The thermal models that were developed and verified were accurate predictors of inflight temperature performance. Analogous approaches are recommended for future long life missions to the outer planets.

7. ACKNOWLEDGEMENTS

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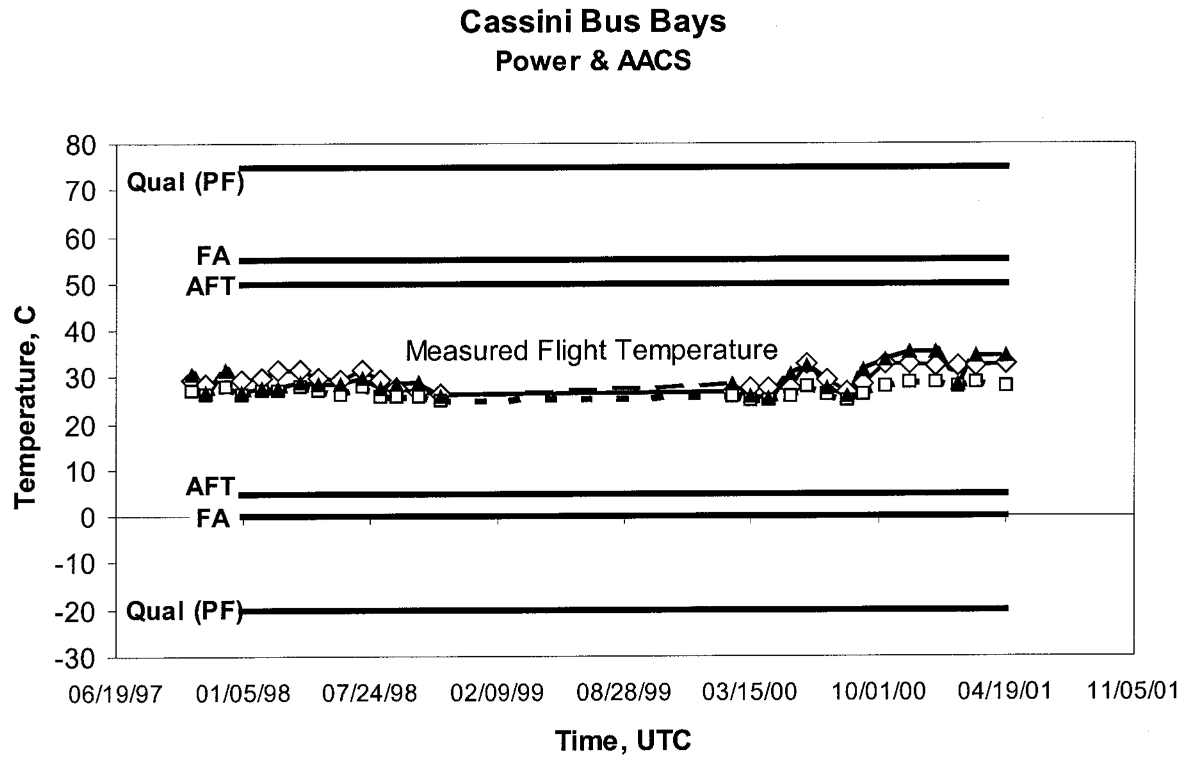

Figure 7. Representative Temperature Profiles for Bus Bays

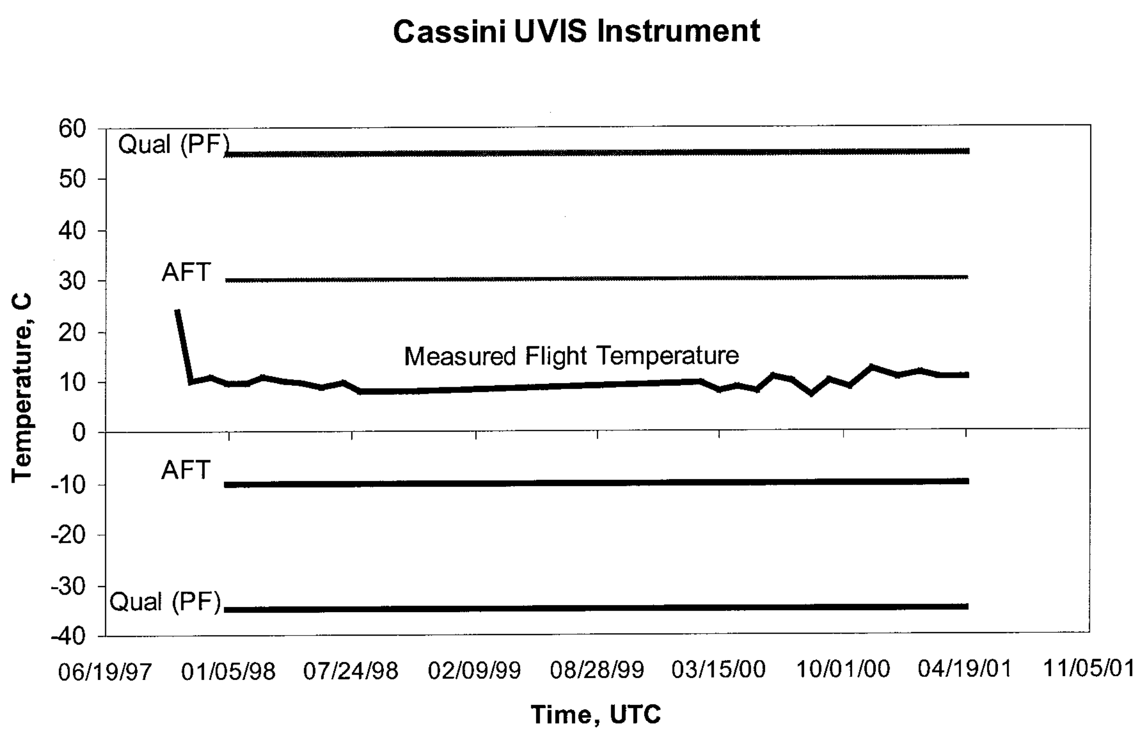

Figure 8. Representative Temperature Profile for Externally Mounted Science Instrument